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REVIVING AND UPGRADING OF THE eP DEVICE

IDAYKIS RODRIGUEZ AND DOUGLAS W. HIGINBOTHAM

ABSTRACT

At Thomas Jefferson National Accelerator Facility, an electron beam is used to probe the fundamental properties of the nucleus. In these experiments, it is essential to know the precise energy of the beam. An important instrument along the beamline to measure the beam energy is the eP device. The device measures the scattered electron angle and the recoil proton angle of an elastic collision. From these angle measurements, the beam energy can be calculated. Many eP device components such as computer software, controls, and mechanical parts needed to be upgraded and/or replaced in order for the eP device to be operational again. A research study was conducted of the current hydrogen target and its properties as well as alternate targets for better performance. As the maximum electron beam energy incident on the eP device will soon be upgraded from 6 GeV to 12 GeV, an analysis was also done on potential changes to the position of the electron and proton detectors in order to accommodate this change. Calculations show that for the new energy upgrade, electron detectors need to be positioned at 5° above and below the beamline to measure the energy of 12 GeV. New proton detectors need to be placed at an angle of 49.2° above and below the beamline to measure energies of 6.6 GeV and 8.8 GeV. With these changes the eP device will measure the range of new energies from 2.2 GeV to 12 GeV. From the target research studies it was found that a carbon nanotube mixture with polypropylene could be the ideal target for the eP device because of its high thermal conductivity and its high hydrogen content. The changes made to the eP device demonstrate the importance of continued research and new technologies.
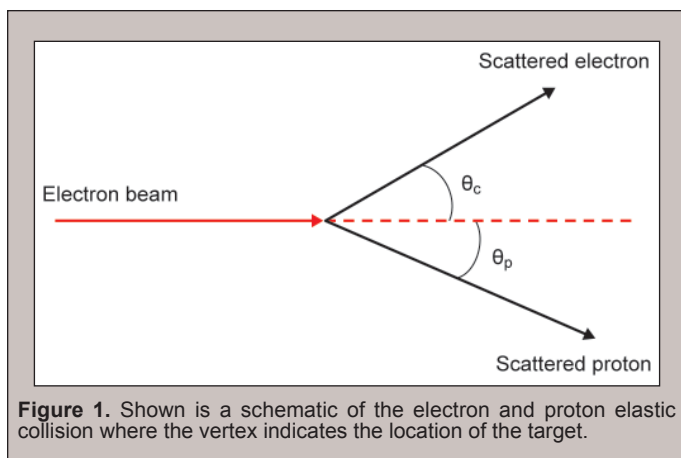
INTRODUCTION

Thomas Jefferson National Accelerator Facility, also known as Jefferson Lab, hosts some of the most innovative experiments in nuclear physics. Jefferson Lab is a United States Department of Energy National Laboratory dedicated to basic research into the fundamental properties of the atomic nucleus. Experiments conducted within the experimental halls use a high-energy electron beam to probe the nucleus. Jefferson Lab's electron beam currently can reach a maximum energy of about 6 billion electron volts (6 GeV) and a proposed upgrade will increase the maximum energy to 12 GeV. For many experiments, accurate and precise measurements of the beam's energy need to be made.

The energy of the electron beam can be measured by several different methods. A simple method of measurement is through elastic scattering. Elastic scattering occurs when one particle collides with another and then both scatter with the energy and momentum of the system conserved. The simplest elastic reaction is between an electron and a proton, denoted as *H(e,e′p)*. In this reaction, an incoming electron collides with a hydrogen nucleus and they scatter in different directions, as shown in Figure 1. The beam energy E is determined by measuring the scattered electron angle θ_e and the recoil proton angle θ_p in the elastic collision using the following formula:

$$E = M_p \frac{\cos(\theta_e) + \sin(\theta_p)/\tan(\theta_p) - 1}{1 - \cos(\theta_e)} + \Theta \frac{m_e^2}{E^2}$$

where M_p is the mass of the proton and m_e is the mass of the electron [1]. In practice, this is done with the Jefferson Lab eP device which makes use of this formula by precisely measuring the scattered electron angle and the recoil proton angle from a thin hydrogen rich target.

Figure 1. Shown is a schematic of the electron and proton elastic collision where the vertex indicates the location of the target.

Figure 2. Schematic layout of the eP device showing example scattered electron and proton tracks. Electrons are detected in silicon-strip detectors (SSD), scintillator (S3), and a Cherenkov for particle identification. Proton are detected in silicon-strip detectors (SSD) and a pair or scintillators (S1 & S2) which can identify protons by time-of-flight.

Figure 3. Shown is a schematic of the polypropylene rotary target system along with the location of the ceramic bearings.
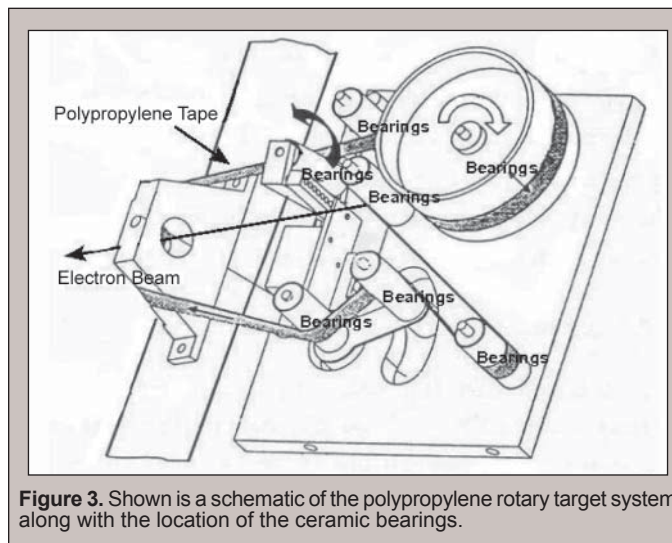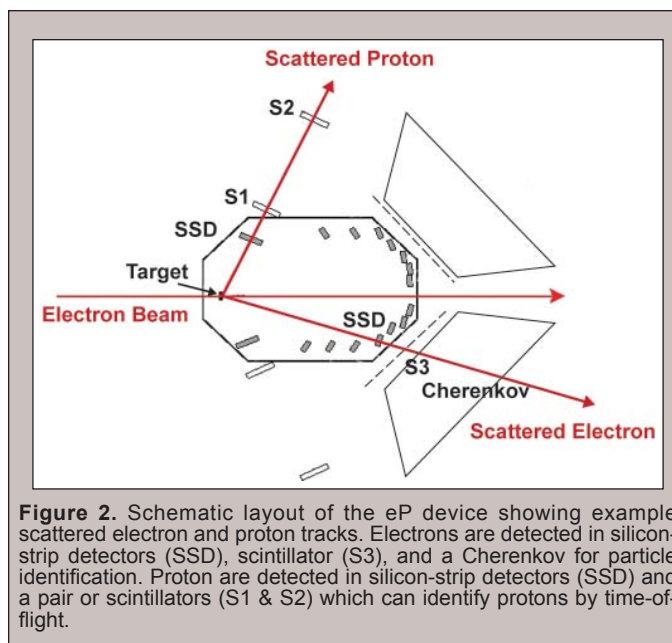
MATERIALS AND METHODS

The eP device is composed of three types of particle detectors to identify the electron-proton elastic collision: scintillators, silicon strip detectors, and Cherenkov detectors. Scintillators, which produce light when a particle passes through them, are attached to photomultiplier tubes (PMT) that transform the light into amplified electrical signals that can then be analyzed. Silicon micro-strip detectors are high-resolution spatial detectors ideal for identifying the position of the particles. The third kind of particle detector used in eP is Cherenkov detectors, which are chambers filled with gas. Cherenkov light is emitted and detected by PMTs when a charged particle moves faster than the speed of light in the gaseous medium [2] and is used to identify the relativistic electrons.

All detectors in the eP device are strategically placed at specific angles to detect elastically scattered particles. The scintillator's position coincides with the solid angle of the silicon strip detectors (SSD) within the eP device as shown in Figure 2. Scintillators S1 and S2 detect charged particles at a fixed angle of 60° detect charged particles and, by measuring the time between S1 and S2, can determine by time-of-flight if the particle is a proton. A coincidence between the S1 and S2 scintillators, a corresponding electron S3 scintillator, and the Cherenkov detector must happen simultaneously for an event to be counted. The eP device is thus designed to detect the electron-proton elastic collisions and any additional reactions which trigger the device will fall within the background noise and will be statistically deleted.

In order to have elastic collisions, the electron beam needs to hit a target. The target for the eP device is a thin film of polypropylene (C_3H_6). The device is designed for the electrons to elastically collide with a proton in a hydrogen nucleus. Certain polymers, like polypropylene, have the high hydrogen ratio that is needed in a target but are unstable in vacuum and melt if the electron beam passes continuously through one spot. The target control was designed to keep the polymer film constantly moving to keep it from melting. The melting is caused by heating due to energy loss as particles travel through matter. The energy that the electrons lose as they pass through the hydrogen target transforms into heat at a rate defined by the Bethe-Bloch equation [3]. To keep the heat generated by an electron beam passing through from melting the target, material must be thermally conductive or have a high melting point. Polypropylene, which has been used as the eP target, has neither of these properties and can melt in the electron beam extremely easily. Thus, finding a better thin target material became the second part of upgrading the eP device.

RESULTS

Reviving the eP Device

The eP device was built over ten years ago [1] and had not been operated successfully for several years. To revive the eP device, extensive upgrades and repairs were done to the machine and to its computer. The computer controls all of the mechanical functions of the eP device and also records the data. The original computer was obsolete and needed to be replaced. The programs and software were transferred from the old computer to the new computer, though there were some difficulties in running the data acquisition

program. This program, CODA, was reviewed and debugged to run on the new computer.

Mechanical parts of the eP device, such as bearings, were checked and replaced. The bearings are part of the target rotary system as seen in Figure 3. The target film rolls on the bearings, which are powered by a small motor on the largest of the cylinders. The bearings used were ceramic ball bearings with steel races. In general, steel is a material that at a microscopic level still has edges and ridges. When rough surfaces rub together, friction will deaden the motion quickly. Any part of the bearing that is made with steel will require some type of lubricant for smooth rolling and to give the bearings a longer lifespan. But for polypropylene, the target rotary system is inside a very high vacuum system and any type of grease or lubricant can disintegrate at low pressures, leaving the steel bearings without lubrication. The old steel bearings were discarded and more robust bearings were used. The replacement bearings were made with ceramic balls on ceramic races since this type of bearing does not require a lubricant and thus works well in vacuum [4]. This new, more efficient and tolerant ceramic bearing should keep the rotary system operational for much longer periods of time before needing maintenance.

Studies of Targets

The current eP device target is polypropylene (C_3H_6) due its high ratio of hydrogen to carbon. This is important since the ratio of hydrogen to other materials in the eP target directly affects the signal to noise ratio of eP device measurements. Previous use of this thin polymer as a target has shown it can work for proton-electron scattering; but the films often break, usually during a measurement, and need to be replaced. This led to a research study on alternate targets for the eP device. The ideal target for this elastic scattering experiment would be a thin, solid piece of pure hydrogen that can conduct heat to its edges for cooling and can move in and out of the beam. Since the ideal target is non-physical, compromises must be made.

Organic polymers, such as polypropylene have been widely used as targets for elastic scattering because they have a high hydrogen-material ratio. Naturally, to keep the 2:1 hydrogen ratio, a good alternate could be water. Liquid water has a higher thermal conductivity than polypropylene. The water could be made to flow through a small container so it does not overheat. A similar target has been used in other experiments at Jefferson Lab as seen in Figure 4. The problem with a target like this is the required thickness of the containment material. The thickness of water along with the thickness of the cell walls creates a significant electron beam energy loss and would compromise the precision of the energy measurements.

The organic compound, Kapton® polyimide, was considered for its high melting point [5]. However, Kapton's chemical formula ($C_{22}H_{10}N_2O_5$) [6] shows that hydrogen is lost amongst the other elements. The approximate

1:4 hydrogen ratio for Kapton® polyimide film disqualifies it as an ideal alternative.

A commonly used target material is carbon. It has high thermal conductivity and can resist the electron beam without moving constantly like the polypropylene film. More recently, the popular carbon material has been chemical vapor deposition (CVD) diamonds. In this research study it was found that the properties of CVD diamonds as a backing material for the original polypropylene are exceptional [7]. The only concern for CVD diamond backing is its thickness and the high carbon content decreases the total hydrogen ratio of the target. Carbon still remains the best known material for use in an electron beam; the difference is the form of carbon. As seen in Table 1, the thermal conductivity of carbon nanotubes is twice that of CVD diamonds [8]. Carbon nanotube technology is proving to be a promising field.

A study was done on polymer carbon nanotube composite that shows the ability to blend the two materials and change their physical properties significantly [9]. The experiment only included 10% by weight of carbon nanotubes while 90% of the original organic polymer remained. This means the density of this new material, as well as the hydrogen ratio, are still approximately the same as the
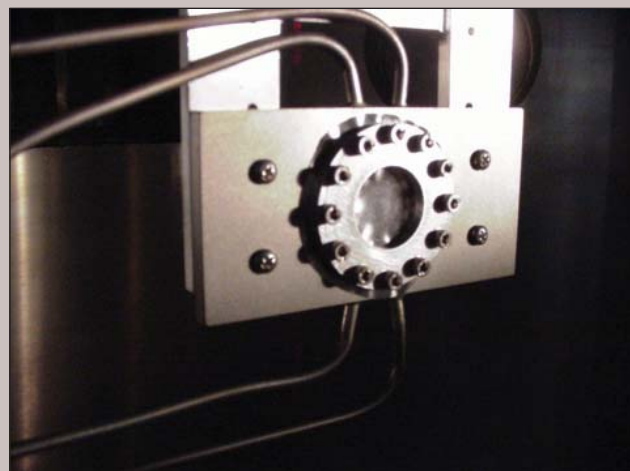
Figure 4. Photograph of flowing water target used in Jefferson Lab experiments.

Target Material	Density (g/cm³)	Thickness (cm)	Ratio of H nucleons	Thermal Conductivity (Wm⁻¹K⁻¹) @300K	Energy loss dE (MeV)
Polypropylene (C_3H_6)	0.95	0.003	2:1	0.20	8.8×10^{-3}
Water (H_2O)	1.00	0.5	2:1	0.60	1.49
Kapton® Polyimide ($C_{22}H_{10}N_2O_5$)	1.42	0.0025	~1:4	0.12	9.6×10^{-3}
CVD Diamond foil	3.52	0.015	0	3320	1.41
C_3H_6 and Carbon Nanotube Mixture	~1.00	~0.005	~2:1	6600	9.3×10^{-3}

Table 1. Shown are the physical properties of the possible target materials. The ideal material is thin to minimize energy loss, has high ratio of hydrogen to minimize background events, and has a high thermal conductivity to prevent melting or boiling of the target. The composite mixture with 90% C_3H_6 and 10% carbon nanotubes clearly best satisfies these requires.

original polymer. If such a composite blend can be manufactured with polypropylene film, then this polymer carbon nanotube composite would be the ideal target, not only for the eP device, but also for many elastic scattering experiments. A summary of the physical properties of all these targets is given in Table 1.

Upgrade Proposal

Scientists are trying to discover new physics as they go deeper into the proton to learn more about quarks. Quarks manifest themselves at very small scale, less than a femtometer. In order to study physics phenomena at such a small scale, large beam energies are needed since the de Broglie wavelength is inversely proportional to the momentum of the particle. Therefore, Jefferson Lab has proposed to upgrade the accelerator facility from a 6 GeV to a 12 GeV. Along with the changes of the beam energy, changes in the eP energy calibration device also need to be done.

The eP device has electron detectors at angles of 9.5°, 12.25°, 15.5°, 24.0°, 35.5° and 38.5° symmetric about the beamline. The position of the electron detectors is determined by the elastic scattering equation for a fixed proton angle of 60°. The positions of the electron detectors are currently designed to measure a range of energy from 0.5 GeV to 5.5 GeV. By manipulating the equation to have the proton angle fixed, it becomes evident that as the energy increases, the scattered electron angle decreases.

The desired energies for the 12 GeV upgrade are 2.2, 4.4, 6.6, 8.8, and 12 GeV. The current geometry of the eP device only allows energies of 2.2 and 4.4 GeV to be detected with a fixed proton angle of 60°. It is proposed to make two major changes to the position of four electron detectors in order to detect the whole range of desired energies. In order to reuse as much equipment as possible, it is proposed to move the two electron detectors from the 30.5° positions symmetric about the beamline to a 5.0° position

Figure 5. The points indicate the eP energy acceptance at a proton angle of 60° and for the proposed 49.2°. The electron angle of 5° will require installing a new detector. The vertical lines indicate the available energies after the accelerator upgrade (2.2, 4.4, 6.6, 8.8, and 11 GeV) and show that the proposed changes will cover all future energies.
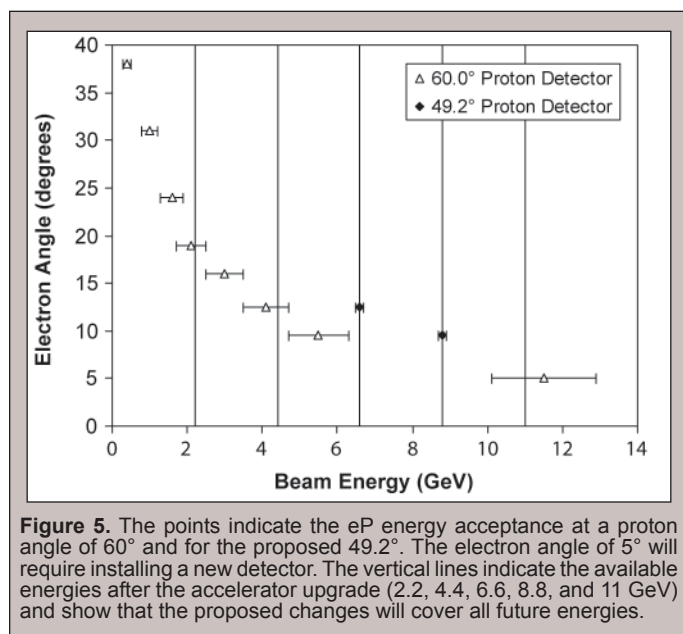
symmetric about the beamline. They would detect the 11 GeV electrons. It was calculated that given the electron angle, both 6.6 GeV and 8.8 GeV could be detected at the single proton angle of 49.2°. It is also proposed to move the remaining electron detectors from the 38.5° to the 49.2° positions symmetric about the beamline. Given this new proton angle of 49.2°, the electrons scattered from beam energies of 6.6 GeV and 8.8 GeV will be detected at 12.25° and 9.5° respectively as seen in Figure 5. The newly upgraded eP device will have an energy detecting range from 1.3 GeV through 6 GeV, and 6.6 and 8.8 GeV exactly, and 10.1 GeV through 13 GeV. These relatively minor changes to the eP device transform it to a useful device for current experiments and future experiments at higher energies.

CONCLUSION

The results show that the eP device can be a proficient energy calibration device. The new upgrades and changes in the computer control system, as well as the mechanical parts, will make the eP device more efficient. The substitution of full ceramic bearings for steel-ceramic ball bearings will reduce maintenance on the target rotary system because ceramic bearings are more effective in a vacuum environment. From the research done on targets, it is evident that the new polymer carbon nanotube composite may be the best thin hydrogen target for elastic scattering experiments. Further research of carbon nanotubes as electron beam targets is needed, but the properties of the polymer carbon nanotube composite show that it may be an ideal target. Testing of the eP device with its new detector upgrade is to be pursued, to determine how accurately and precisely the new electron detectors at 5.0° and the new proton detectors at 49.2° will measure the incoming beam energy. Reviving the eP device demonstrated the importance of continued research and new technologies.

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